The new CIRIA C760 Observational Method implementation framework and its potential application to projects in Singapore

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ABSTRACT: Despite its formalisation for use in geotechnical design for nearly 50 years, the Observational Method (OM) has not been widely adopted. The new Construction Industry Research and Information Association (CIRIA) publication C760 (Gaba *et al.*, 2017) clarifies the terminology underpinning the OM together with a robust new framework that is compliant with Eurocodes and international best practice for its implementation with clear unambiguous guidance. The OM can be incorporated into any contract. However, it is likely to be most effective when used as part of a deliberate design and procurement strategy and associated contractual arrangements that promote, encourage and facilitate strong and close collaboration and partnering between all of the key parties engaged on the project, from an early stage. This typically results in significant economic and programme benefits and improved risk and safety management outcomes.

This paper outlines the new OM framework and its application to achieve these significant benefits, with reference to case histories. In so doing, the paper stresses the importance of clarity between the roles and responsibilities of all of the key participating parties and their necessary interfaces and, in this context, discusses the regulatory system specifically applicable in Singapore.

Examples of uses are discussed and preliminary recommendations are made for the future application of the OM in Singapore within this new framework.

1 INTRODUCTION

1.1 Background

The Observational Method has been used for many centuries, but it was first formalised for geotechnical design by Peck (1969). The method has been revisited since, most notably by Powderham (1994), Nicholson *et al*. (1999) and Gaba *et al*.

(2003). Despite the clear benefits in terms of economy, programme reductions, better collaboration and partnering, and improved risk and safety management, there have remained some reservations to employ it widely.

The principal reasons cited for inhibited application of the OM were the inconsistent definitions, terminology and approaches adopted by the above researchers and practitioners and the lack of a coherent framework that was compliant with Eurocodes and comparable international standards and codes of practice to permit its application and acceptance by relevant approving and checking bodies. This paper addresses these issues.

1.2 Historical development of the OM

Since the formalization of the OM, a range of definitions and approaches have been applied to its use. These have traditionally advocated its use *ab initio,* where the use of the OM is planned from the start of the project. However, some of these approaches have been inconsistent in their respective applications and this has caused confusion. For example, CIRIA R185 (Nicholson *et al.*, 1999) significantly departed from the *ab initio* approach to the OM advocated by Peck (1969): instead of starting with a "most probable" design, CIRIA R185 proposed to start with a "characteristic" design with a "most probable" design as a possible modification. Powderham (1994) further confused the matter by introducing the concept of progressive modification using "more probable" design. These different approaches reflect varying treatment of the balance between risk and opportunity. Peck's definition viewed the application of contingency measures as risk mitigation, whereas Nicholson *et al.* (1999) and Powderham (1994) viewed the application of modification as an opportunity. A detailed discussion of this is provided in Hardy *et al.* (2017) and the reader is referred to that publication for more information.

1.3 CIRIA C760

Since its publication, C580 (Gaba *et al.*, 2003) *Embedded retaining walls – guidance for economic design* has been amongst the best-selling and most downloaded design guidance publications by CIRIA. It has been used in the UK and internationally for major projects involving the retention of deep excavations, design of underground structures and the assessment of associated ground movements and building damage. The most significant contribution made by CIRIA C580 was the articulation and application of the Limit State Design method to embedded retaining walls. A detailed review and revision of CIRIA C580 has recently been completed with very wide international consultation, involvement and participation across all parts of industry including major clients, project funders and promoters, insurers, contractors, academia and design consultancies.

CIRIA C760 (Gaba *et al.,* 2017), supersedes CIRIA C580 and provides detailed updated guidance on the geotechnical and structural design of embedded retaining walls and their support systems in full compliance with Eurocode requirements, consistent with international best practice. It is also the first publication that clarifies the terminology underpinning the OM and establishes a robust new framework advocating four distinct approaches for its implementation within the Eurocode environment to achieve significant economy in material savings and reduced programme durations.

This paper describes the new CIRIA C760 OM terminology and framework and illustrates the application of each of the above approaches with reference to specific case histories drawn from projects principally undertaken in the UK and Singapore. It also clarifies the roles and responsibilities of the project participants necessary for the successful implementation of the OM and makes preliminary recommendations for the application of OM on future projects in Singapore, cognizant of the specific regulatory system that applies in Singapore.

2 ROLES AND RESPONSIBILITIES OF THE PROJECT TEAM

2.1 Procurement and contractual arrangements

The OM can be incorporated into any contract. Before embarking on its implementation, it is imperative that all members of the design and construction team have a good understanding of the overall objectives and key criteria and that each member of the project team is aware of individual and collective responsibilities, and the necessary interfaces between their respective roles.

The OM is therefore most effective when used as part of an overall procurement strategy and contractual arrangements that promote, encourage and facilitate strong and close collaboration and partnering between all of the key parties engaged on the project, from an early stage. In this way, all parties can be appropriately motivated and can share in the benefits achieved from its successful implementation.

2.2 Client

The client has the most to gain from the use of the OM. In addition to the potential reduction in material and construction costs associated with reduced programme duration, the structure/facility can be brought into use more quickly with obvious fiscal benefits in terms of generating income streams, or reduced interest payments on loans associated with project funding, etc.

Whichever procurement method is adopted, the client should ensure that the designer and contractor employed to deliver the project have the necessary technical expertise, capability and experience to implement the OM.

2.3 Designer

The designer should be confident in their understanding of the ground behaviour at the site and the particular requirements of applying the OM. The correct implementation of the *ab initio* OM requires the designer to have understood the range of potential behaviours and to have a set of contingency/modification measures developed before the start of construction, if any of these arise. The *ipso tempore* application of the OM requires the designer to develop such contingency/modification measures based on reliably monitored actual performance during construction. The terms *ab initio* and *ipso tempore* are defined in Section 4.1 of this paper.

The designer should remain an integral part of the project delivery team until completion of construction, continually working closely with the client and the contractor to ensure safety is maintained at all times.

2.4 Contractor

To successfully implement the OM, the contractor should remain engaged with the designer throughout the project programme and be prepared to implement the contingency or modification measures developed by the designer for the range of expected behaviours. In addition, the contractor should ensure that the necessary instrumentation and monitoring equipment is protected and accessible at all times.

Successful implementation of the OM requires a strong, interactive and professional relationship between the contractor and the designer.

2.5 Independent checking and approving bodies

When considering the application of the OM, it is imperative that any independent checking or approving body (e.g. independent assessors, supervisors, or an organization) has a level of technical understanding commensurate with that of the designer. The technical demands placed on such independent checking or approving bodies will be equivalent to those on the designer. The checker or approving body should be confident regarding the effectiveness of the contingency or modification measures developed by the designer and adopted by the contractor, the trigger levels and response plan, and should remain involved throughout construction.

3 EUROCODE 7 REQUIREMENTS

Eurocode 7 (EC7) explicitly includes provision for using the OM and requires the following conditions to be met before construction starts in relation to the retention of a deep excavation:

- *"Acceptable limits of behaviour shall be established"*

  This requires appropriate monitoring of the retaining wall and its support system to measure wall deflection and profile, ground movements (due to wall installation, deflection and other effects e.g. dewatering), and prop/anchor loads. Serviceability Limit State (SLS) and Ultimate Limit State (ULS) limitations on deflections/movements relating to the tolerance of nearby structures/utilities to accommodate such movements must be considered.

- *"The range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits"*

  This requires the designer to consider ground behaviour particularly in relation to speed of construction (e.g. undrained behaviour versus drained behaviour), ground anisotropy, structural behaviour of the wall and its support system (e.g. material properties and the behaviour of connections between the wall and props/anchors and between individual wall elements), parameter selection (e.g. variability and reliability in determining characteristic, most probable, re-calibrated values).

- *"A plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully"*

  This requires an early verification phase during the initial stages of construction on site to confirm that actual behaviour is within acceptable limits.

- *"The response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system"*

This requires an efficient process that reviews/assesses/back analyses the monitoring data to enable the instrumentation and monitoring system to be adapted/developed further to facilitate appropriate decisions to be made and implemented in a timely manner.

- *"A plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behaviour outside acceptable limits"*

  This requires the designer to have developed alternative construction sequences and/or additional support measures as contingencies in this eventuality, to restore the performance of the retaining wall and its support system to lie within acceptable limits.

4 NEW CIRIA C760 OM TERMINOLOGY AND FRAMEWORK

4.1 Terminology

CIRIA C760 (Gaba *et al.*, 2017) brings together, clarifies and builds on the previous work undertaken on the OM, putting this in its proper context within a new robust framework for application. It defines four approaches in two categories, as follows:

- *Ab initio* (translation from Latin: "from the start")
  Approach A (optimistically proactive)
  Approach B (cautiously proactive)

- *Ipso tempore* (translation from Latin: "in the moment")
  Approach C (proactive modifications)
  Approach D (reactive corrections)

The OM can be applied in one of two ways:

1. When the information from the completed construction at one location informs the design of the same or similar structures at a nearby location. This can be particularly useful for long linear retaining structures used, for example, in road or railway construction. In this case, the application of the OM can be contemplated from the outset; or

2. When the knowledge gained through observations at the early stage of an excavation at a location can be used to modify the excavation sequence and temporary support system at that location in later stages.

In the first case, back analysis of data to derive reliable most probable parameters can be adopted in design to realise savings from the outset (Approach A). In this instance, there is maximum potential for savings in materials associated with the wall and its support system and reduced construction duration.

In the second case, the design of the wall for the initial stages could benefit from the experience gained from the early stages of construction allowing the *ab initio* method to be applied with confidence and a modified construction sequence based on most probable parameters to be adopted for the later stages (Approach B) yielding potential savings associated with reduced wall support requirements and reduced construction duration. Similar savings can also be made through *ipso tempore* modification of the design as the construction progresses, providing movements are found to be within acceptable limits during the initial stages of construction (Approach C). Or, conversely, contingency methods can be employed to ensure that movements do not exceed acceptable limits (Approach D). Table 1 summarises the key features of these possible approaches to the application of the OM.

The sections below describe each of these approaches in more detail.

Table 1: Summary of OM approaches from CIRIA C760 (Gaba *et al*., 2017)

	***Ab initio* (from the start)**		***Ipso tempore* (in the moment)**	
	A *Optimistically proactive*	*B* *Cautiously proactive*	*C* *Proactive modifications*	*D* *Reactive corrections*
When implemented	The OM is planned from project inception		Starts with conventional design with no explicit intention of applying the OM	
Back analysis requirements	Necessary before construction starts from available reliable and relevant case study data	Preferable, but not essential	Necessary – from assessment of initial construction stages	
Analysis assumptions for design of the wall and its support system	Wall embedment, design and construction sequence in accordance with EC7 'design by calculation' method adopting 'most probable' parameters	Wall embedment depth, design and construction sequence in accordance with EC7 'design by calculation' method adopting characteristic parameters	Wall embedment, design and construction sequence in accordance with EC7 'design by calculation' method adopting characteristic parameters	
Implementation	Most probable wall design and associated construction sequence implemented on site Alternative construction sequence fully developed in accordance with EC7 'design by calculation' adopting characteristic parameters for use as contingency, depending upon the actual performance of the wall and its support system	Characteristic wall design and associated construction sequence implemented on site Alternative construction sequence fully developed in accordance with EC7 'design by calculation' method adopting 'most probable' parameters for use on site, depending on actual performance of the wall and its support system	Monitoring, observations and back analysis during construction show wall performing better than anticipated. Ground, material and structural parameters and ground and analytical models re-calibrated on this basis. Construction sequence modified and fully developed in accordance with EC7 'design by calculation' method adopting 're-calibrated' parameters	Monitoring and observations during construction show wall not performing in accordance with design predictions Additional measures put in place to prevent breach of a limit state, e.g. damage to nearby structures or to prevent catastrophic collapse
Advantages and possible savings	Maximum potential for savings in materials and construction programme duration	Savings in construction programme duration but no wall material savings, although some savings in materials may be possible due to reduced wall support requirements.	Possible savings in wall support system during excavation in front of the wall by modifying construction sequence and support system requirements. Only likely to be feasible on large projects with long construction duration	Provides a systematic approach to implementation of remedial contingency measures/actions

4.2 Ab initio

The OM is implemented from the start of the design process and requires a range of possible ground behaviours to be considered. It should be noted that once the retaining wall has been installed on site, it cannot be changed. The designer must therefore decide from the outset which approach to take – Approach A or Approach B. Whichever approach is adopted, it is important that the client and the contractor are also actively engaged in making that decision and fully involved in its implementation.

Approach A (optimistically proactive)

This is analogous to the first part of the *ab initio* method proposed by Peck (1969). The design of the retaining wall and its support system is undertaken assuming a construction sequence based on most probable ground and structural behaviour to determine the wall's embedment depth and structural capacity and most probable deflections and ground movements. It is this wall that will be installed at the site.

For this most probable wall embedment and structural capacity, the designer is also required to develop a modified construction sequence and additional wall support arrangement assuming characteristic ground and structural behaviour (in accordance with the "design by calculation" method defined in EC7) that confirms the adequacy of the most probable wall embedment depth and structural capacity and determines the characteristic SLS wall deflections and ground movements. This is the fully developed contingency for implementation in the event that the results of the performance monitoring during the early verification construction stages on site indicate that it would not be appropriate to continue with the most probable approach.

Trigger limits are set to monitor performance relative to the characteristic and most probable predictions to enable such a decision to be made at the end of the verification stages as to which construction sequence should be adopted for the remainder of the construction, see Figure 1.

A successful application of Approach A at the Harris Bank excavation in Chicago is described by Peck (1969).

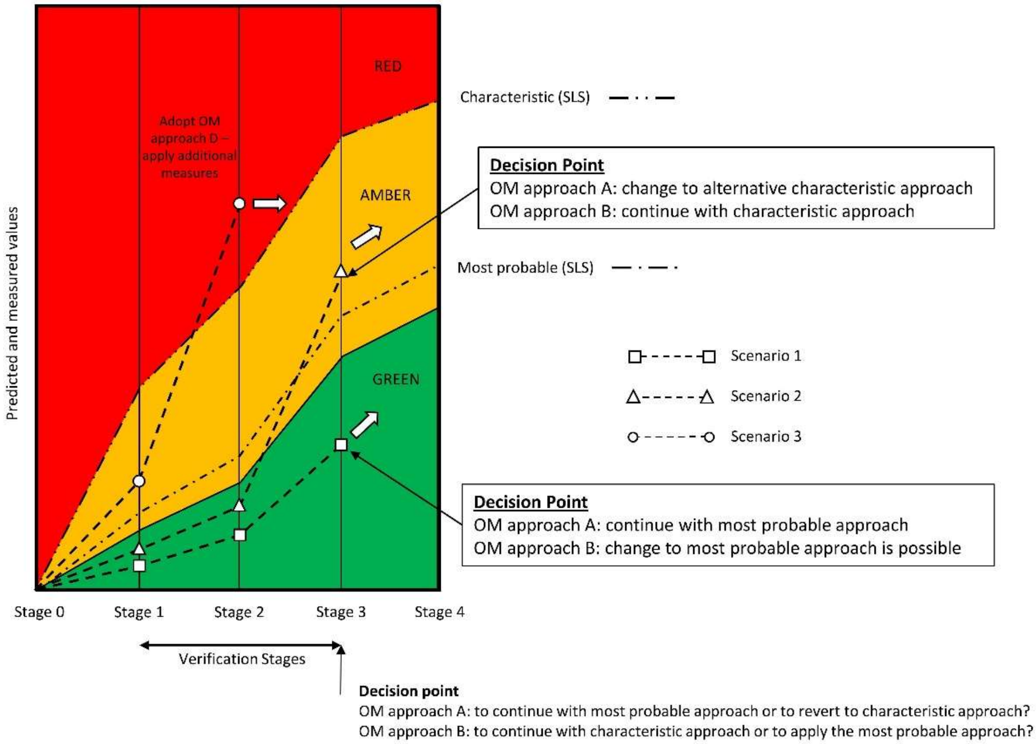


Figure 1: Trigger limits for *ab initio* Approaches A & B from CIRIA C760 (Gaba *et al.,* 2017)

Approach B (cautiously proactive)

The design of the retaining wall and its support system is undertaken assuming a construction sequence based on characteristic ground and structural behaviour (in accordance with the "design by calculation" method defined in EC7) to determine the wall's embedment depth and structural capacity and characteristic SLS deflections and ground movements. It is this wall that will be installed at the site.

For this characteristic wall embedment and structural capacity, the designer is also required to develop a modified construction sequence and reduced wall support arrangement assuming most probable ground and structural behaviour that confirms the adequacy of the characteristic wall embedment depth and structural capacity and determines the most probable wall deflections and ground movements. This is the fully developed alternative for implementation in the event that the results of the performance monitoring during the early verification construction stages on site indicate that it would be appropriate to continue with the most probable approach.

Trigger limits are set to monitor performance relative to the characteristic and most probable predictions to enable such a decision to be made at the end of the verification stages as to which construction sequence should be adopted for the remainder of the construction, see Figure 1.

This approach was successfully undertaken at Batheaston Bypass, UK (Nicholson *et al.*, 1998) to achieve significant cost and programme savings.

4.3 Ipso tempore

The application of the *ipso tempore* method differs from the *ab initio* method in that it is not planned from the beginning of the project, but rather it is adopted during construction after the wall has been installed.

The design of the retaining wall and its support system is undertaken assuming characteristic ground and structural behaviour (in accordance with the "design by calculation" method defined in EC7) to determine the wall's embedment depth and structural capacity and characteristic SLS wall deflections and ground movements, with appropriate trigger limits set relative to this to monitor actual performance on site.

Two scenarios are possible: Approach C and Approach D.

Approach C (proactive modifications)

In this scenario, the wall is performing better than anticipated by the designer during the initial construction stages and a proactive decision is made by the project team to modify the construction sequence for the remaining construction to achieve programme savings. As is the case with Approach B, there is no opportunity to make savings on wall materials, as the wall will have already been installed at the site. However, the significant difference between Approaches B and C is that when construction started on site, in Approach C there was no intention to implement the OM and therefore no alternative construction sequence was fully developed from the outset of the project. In view of this, a thorough audit of the wall's performance in relation to the actual construction sequence up to that point in time is necessary before a rigorous back analysis of the wall can be undertaken to "re-calibrate" the parameters assumed in design. Details of such an audit and the associated back analysis to derive re-calibrated parameters are set out in detail in CIRIA C760 (Gaba *et al.*, 2017). These re-calibrated parameters are then used to determine an improved construction sequence with associated revised trigger limits for the subsequent construction stages, see Figure 2.

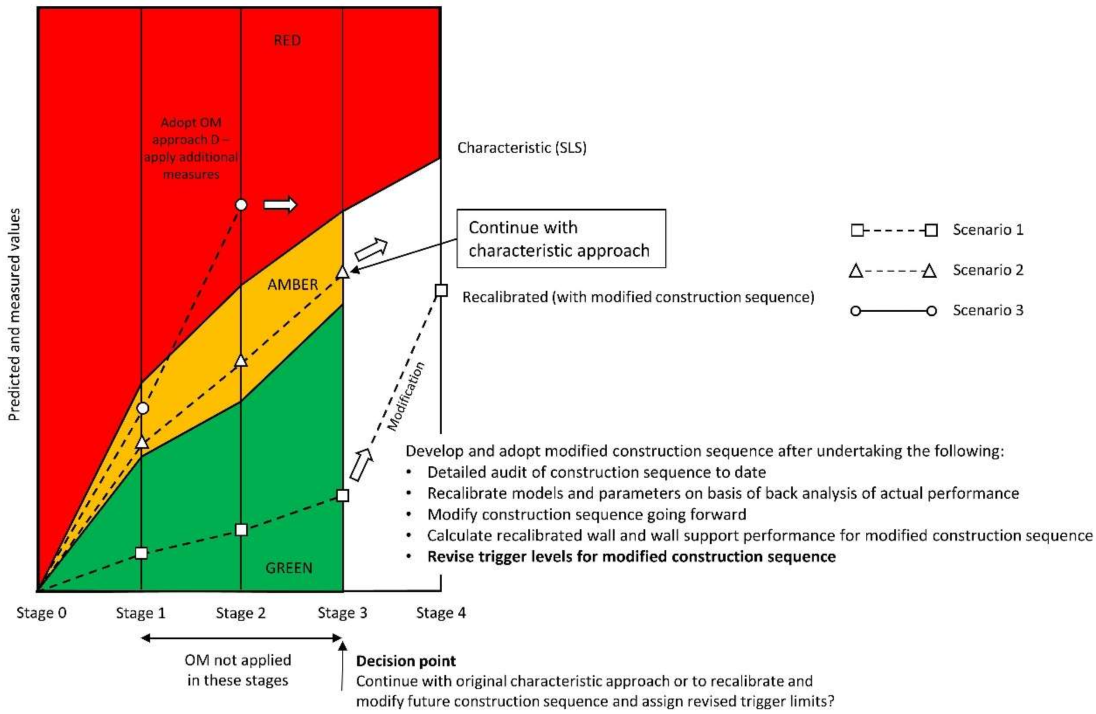


Figure 2: Trigger limits for *ipso tempore* Approaches C & D from CIRIA C760 (Gaba *et al.*, 2017)

Approach C was recently successfully undertaken in the UK for the Crossrail Tottenham Court Road Station Western Ticket Hall (Yeow *et al.*, 2014 and Chen *et al.*, 2015).

Approach D (reactive corrections)

In this scenario, the actual wall performance is of concern to the designer and reactive intervention is required to prevent a SLS or ULS occurring. This approach is analogous to the "best way out" approach proposed by Peck (1969).

A good example of the application of Approach D is described by Nicholson (1987) and Gaba (1990) and is discussed further in Section 5.3 of this paper.

5 APPLICATION OF OM IN SINGAPORE

5.1 Design overview

EC7 for temporary and permanent retaining wall design has been adopted in Singapore. Designs are routinely carried out using a limit state approach in accordance with SS EN 1997-1: 2010 Eurocode 7: Geotechnical design - Part 1: General rules, in conjunction with the Singapore National Annex (NA) to EC7, NA to SS EN 1997-1: 2010. Additionally, some clients require limit equilibrium checks to be carried out.

In accordance with the NA to SS EN 1990: 2008, the indicative design working life is taken as 10 years for temporary structures and 120 years for permanent structures. It is common practice to assume the same design properties and groundwater conditions for both temporary and permanent works design.

The following Ultimate Limit States (ULS) are considered in design:

- EQU: loss of static equilibrium of the structure or the ground, in which the strengths of the structural materials and the ground are insignificant in providing resistance;
- STR: failure or excessive deformation of the structure, in which the strength of the structural materials is significant in providing resistance;
- GEO: failure or excessive deformation of the ground, in which the strength of the soil or rock is significant in providing resistance;
- UPL: loss of equilibrium of the structure or the ground due to uplift by water pressure (buoyancy) or other vertical action; and
- HYD: hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients.

ULS analysis is undertaken to Design Approach 1 for Combinations 1 and 2 as required in NA to SS EN 1997-1: 2010. The following are the Combinations considered:

- Combination 1 (factored actions): A1 + M1 + R1
- Combination 2 (factored soil): A2 + M2 + R1

In the design of propped excavations, typically the STR, GEO and UPL/HYD checks govern. For Serviceability Limit State (SLS) design, movement of the retaining structure which may affect the appearance or efficient use of the structure or nearby structures or services which rely on it are considered. Where partial factors are used for SLS analysis, they are set as all equal to unity as per SS EN 1997-1:2010, Section 2.4.8 (2).

One of the key considerations in the design and construction of retaining systems is to maintain wall deflections within acceptable limits to ensure that adjacent structures are not adversely affected by the excavations. Notwithstanding other necessary design checks, the evaluation of the deflection of the retaining walls and the corresponding calculated ground movements are obtained from the SLS analysis.

One of the key variables in the design process is the derivation of soil parameters. When deriving soil parameters the concept of 'characteristic' soil parameters in an EC7 design approach has its constraints in the Singapore context. This is because:

- For Normally Consolidated soft soils 'characteristic' and 'most probable' values are very similar because these soils can be somewhat consistent in their strength and stiffness parameters;
- In some circumstances 'rules of thumb' are still adopted for soil parameters in Singapore; and
- Increasingly for weathered rocks and stiff soils designers have been using less conservative parameters, as deep excavation case history data have started to emerge and the derivation of *in-situ* parameters has become possible through back analysis of available case history data and techniques like geophysics and large sample testing.

5.2 Regulatory system in Singapore

Singapore has a unique regulatory framework centered around a 'PE' system. Design is undertaken by a Professional Engineer (PE) under the regulation of the Building Control Authority (BCA) for a project. Liability rests with an individual PE(s) rather than a company or an organisation. For deep excavations there is an additional requirement for the PE to be specialized in the field of geotechnical engineering. If the PE is not specialized, the PE must jointly prepare the design with a PE who has this specialization.

Mandatory checking of deep excavation design is completed by independent PE(s), or Accredited Checker(s), one of whom must be specialized in the field of geotechnical engineering. Construction is undertaken by a Registered Contractor. Contractor registration is administered by the BCA. Construction supervision is undertaken by PE(s) together with a team of site supervisors. Similarly to design, if the supervising PE is not a geotechnical specialist the works must be jointly supervised by a PE who is a geotechnical specialist.

The overall process must be in compliance with the Building Control Act. The process of design and construction to the Act is shown in Figure 3.

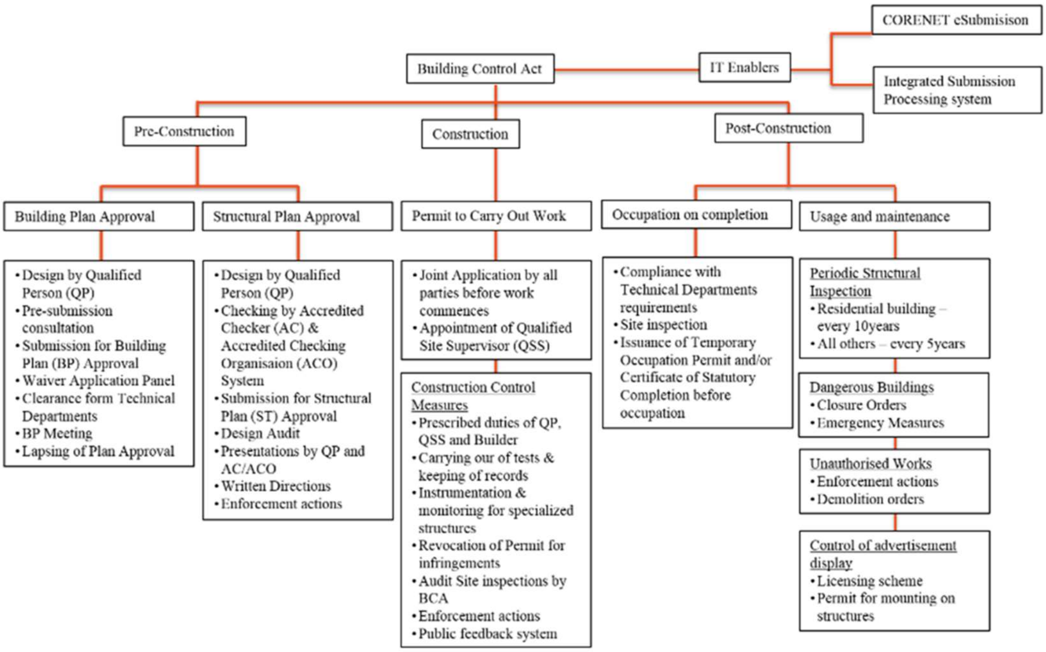


Figure 3: Building Control Act – compliance procedure for design and construction

The system described above, as it is applied for deep excavation works, can result in the following for a particular project:

- there can be up to 2 checking PEs, a structural PE and a geotechnical PE;
- there can be separate design PEs for temporary and permanent works; and
- there can be separate supervising PEs for the construction of the works.

Furthermore, depending on the procurement approach and client preferences, the following may arise:

- The design PEs are employed by the client (build only) or by the contractor (design & build);
- The supervising PEs are employed by either the client or the contractor (procurement method dependent); and
- The supervising PEs may not be permitted to be the design PEs (client preference).

Thus on any part of a project there can be a number of individual PEs responsible, each with a legal responsibility for safety.

Given the size of some projects, designs are submitted for approval across a number of submissions adding further complexity. It is also worth noting that any modification of the design during the construction of the project must go through the checking and approval process each time before implementation.

Implementing OM in Singapore will need to consider this regulatory environment.

5.3 Observations on OM applications in Singapore to date

Considering the two categories and four OM design approaches described in Section 4 above, the following observations can be made in the Singapore context:

Ab initio - Approach A

This would differ significantly from current Singapore practice, in that a design would be developed for the retaining walls and implemented on site based on 'most probable' soil parameters.

Practically this may not be as radical as it first appears. Today in Singapore soil parameters currently adopted in design are in many instances approaching or close to 'most probable' values, particularly as noted above for soft soils. For stiff soils and weathered rocks further work would be required on a project by project basis to establish these 'most probable' parameters.

Establishing wall sizes, forces and wall embedment depths for purely temporary retaining systems based on 'most probable' parameters could practically limit the remedial or recovery measures that can be implemented if actual behaviour on site is worse than predicted. Often in Singapore the retaining systems perform well but groundwater changes or simply the proximity to adjacent structures means that construction sequence changes are necessary. Sizing the walls with Approach A could limit recovery options in those cases.

It would seem feasible and not unsafe to adopt this approach for deep excavations in the right setting (i.e. well understood ground conditions and not in very close proximity to buildings), with appropriate instrumentation and monitoring in place.

Under this Approach a single design for an excavation would be prepared using 'most probable' parameters and approved under the Building Control Act.

We are not aware of any project in Singapore that has adopted this approach, although we are starting to see the use of less conservative perhaps tending towards 'most probable' soil parameters in designs. These are being derived through *in-situ* methods, particularly for stiff soils and weathered rocks. As case histories are emerging and more and more excavations are succesfully completed, designers are adjusting parameters based on their own experiences and observations.

Ab initio - Approach B

This would differ from Approach A above in that a design would be developed for the retaining walls based on 'characteristic' soil parameters in accordance with EC7.

2 strutting designs would be developed, one based on 'characteristic' soil parameters, the other based on 'most probable' soil parameters.

If adopted, in practice 2 strutting designs would have to be approved under the Building Control Act and as the excavation proceeds the designer could adopt either system or a combination of them as the actual observed behaviour is monitored over the initial verification stages of construction.

An approach similar to this was adopted for a recently completed deep excavation project in Singapore. This project required an excavation of over 40m predominantly in the Fort Canning Boulder Bed formation found in parts of Singapore's Central Business District. There was some concern given the lack of experience in this formation that derived 'characteristic' parameters for the soils may be overly conservative given the difficultly in sampling the formation for parameter derivation. Hence, two designs were developed. The particular specification for the project stipulated the following:

'The Contractor shall note that the installation of struts at particular levels or locations may be omitted based on the performance requirements of the retaining system, subject to approval of the Engineer.'

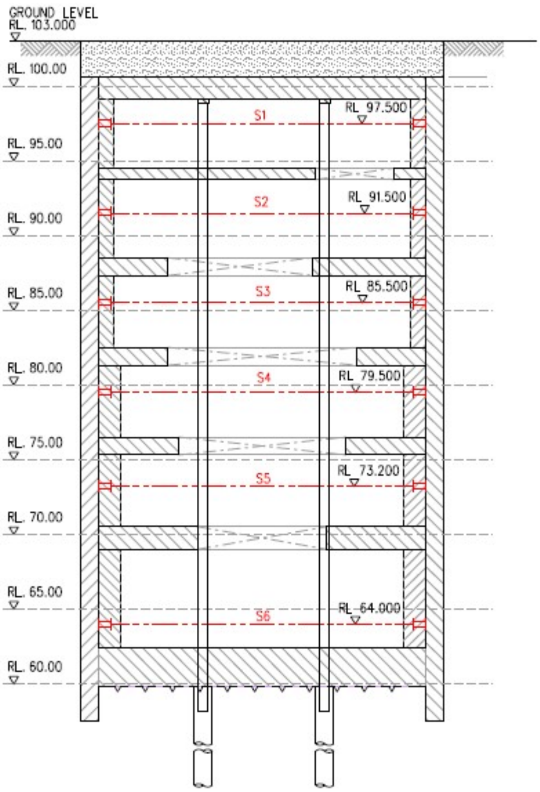


Figure 4: Top-down deep excavation in Fort Canning Boulder Bed, Singapore

The envisaged retaining system is shown above in Figure 4 and could have required up to 6 levels of temporary strutting, S1 to S6. During construction these struts would not require installation if the following was observed:

- Incremental retaining wall movement measured from the previous propping location <12mm;
- Adjacent settlements within predicted limits; and
- Overall wall movement <50mm.

On this project the overall system behaviour was such that none of the 6 temporary levels of struts were installed in the main top down excavation. The project was successfully completed.

The authors consider that this approach could have wide ranging future application in Singapore to optimize construction. Areas of potential application include general strutted excavations and also particular issues that arise in deep excavation design, for example:

- Cantilever movements in soft ground;
- Ground conditions that can be locally clayey or sandy and it is not known with certainty if the ground will exhibit undrained or drained behaviour during excavation (e.g. Old Alluvium layers);
- *In-situ* stiffness of significant fill layers; and
- Designing when *in-situ* soil sampling for testing is difficult to consistently undertake, for example where soils are cemented or are colluvial in form.

Ipso tempore - Approach C

This approach is sometimes adopted in Singapore where statutory approval time permits, although it is rarely labelled as OM.

Typically, this approach has been applied to modify or remove levels of strutting as the wall and surrounding settlement behaviour has been better than predicted in the 'characteristic' design. It is less common to use this approach to modify wall type or sizes through a project.

The approach is characterized by the need to undertake detailed back-analysis of the observed behaviour and predict future behaviour if the construction sequence is modified. Benefits similar to those associated with Approach B can be achieved, but practically there is often not enough float in the construction programme to secure the necessary approvals and permits in time to proceed with this approach.

An example of this approach being undertaken in Singapore was for an excavation being completed predominantly in the weathered Jurong formation in the Central Business District. The project required an excavation of 20m and utilized 3 temporary strut levels, as shown in Figure 5 below. As excavation proceeded below the S1 strut level the observed retaining wall movement was significantly less than predicted.
The back-analysis undertaken showed that the soil layers above the Jurong formation were stiffer than the original design had considered. The designer justified that the S2 strut was not required on the basis of this reliably monitored observed information.

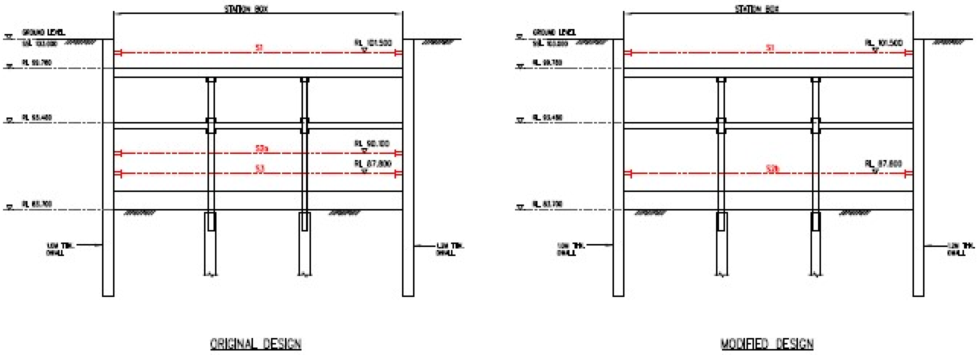


Figure 5: Deep excavation in Jurong Formation, Singapore

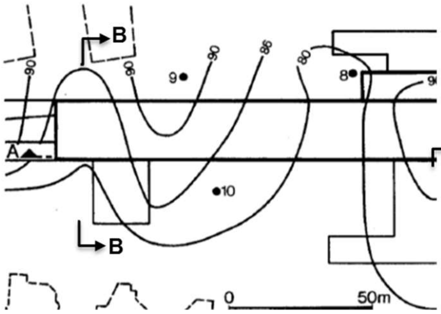
Ipso tempore - Approach D

This approach is sometimes required in Singapore after designs have been approved and site work has started. Typically this has been applied where:

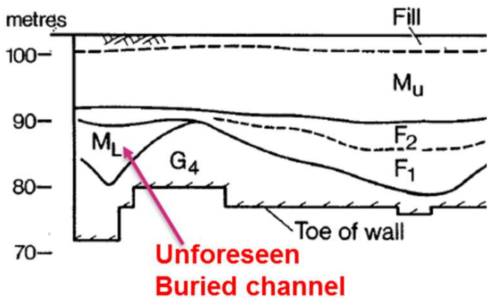
- During predrilling for retaining wall installation unforeseen ground conditions have been identified that have required a change or a modification of the design;
- Retaining wall installation close to an adjacent structure or utility has led to more settlement than was predicted at the time of design, as occurring during that activity. Typically this has occurred where the adjacent structures have been on shallow foundations bearing on fill or soft soils. These settlements are typically induced by vibration, ground loss or groundwater drawdown or a combination thereof during the installation process;
- Ground treatment outside the retaining walls has induced settlements on adjacent structures or utilities. Again the impact of this is typically greater where adjacent structures are supported on shallow foundations;
- Ground treatment inside the excavation for improved stability is sub-standard or incomplete. This is often only observed as the excavation proceeds and must be addressed quickly as it can have implications on the overall stability of the retaining system;
- Generally, the retaining system is performing well but the adjacent building settlement has been excessive, perhaps due to groundwater changes and as such

the designer opts to 'stiffen' the retaining system going forward to ensure the remaining works control future movements to a practical minimum.

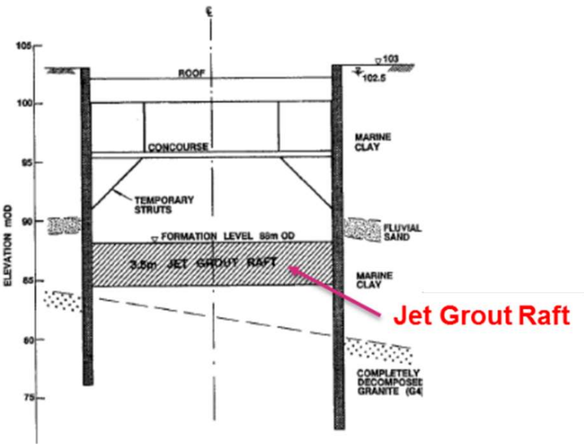
Nicholson (1987) and Gaba (1990) describe a good example of the application of Approach D at Newton Station in Singapore. Here an unforeseen buried channel infilled with marine clay was encountered during diaphragm wall installation and a buried jet grouted raft was designed and successfully installed to provide additional support to the wall below final formation level, see Figure 6.



Station Plan - Top of Decomposed Granite (G4)



Section A-A



Section B-B

Figure 6: Application of Approach D at Newton Station, Singapore (from Nicholson, 1987 and Gaba, 1990)

5.4 Future OM application in Singapore

Adoption of the OM in Singapore must consider a number of factors including:

- Current design methods and approaches, including the use of 'characteristic' or 'most probable' or 're-calibrated' parameters and how these are applied in practice;

- The regulatory requirements in place under the Building Control Act;

- Projects with excavations procured as either 'build only' and 'design and build' projects;

- The complex geological and groundwater conditions that exist in parts of Singapore;

- Most design currently undertaken will assume the same groundwater and soil properties both during construction and in operation; and

- A significant amount of excavation work in Singapore is undertaken in very urban environments with buildings and other structures in close proximity.

Any application of OM in Singapore must consider all of the above. In this context we have considered some possible ways that the OM could be applied within the new C760 OM framework. In considering OM we have considered a number of design scenarios for two ground excavation categories, as follows:

Category α: deep excavations in soft soils where these soils extend below formation

Under this category retaining systems could take one of the following forms:

i. the retaining system is flexible, temporary and 'floating';

ii. the retaining system is flexible, temporary and embedded into a stiff stratum;

iii. the retaining system is stiff, permanent and embedded into a stiff stratum (bottom up construction); and

iv. the retaining system is stiff, permanent and embedded into a stiff stratum (top down construction).

Category β: deep excavations in predominantly stiff soils or weathered rocks

Under this category retaining systems could take one of the following forms:

i. the retaining system is flexible and temporary;

ii. the retaining system is permanent (bottom up construction); and

iii. the retaining system is permanent (top down construction);

Further ground excavation sub-categorization could be made by considering the following:

- Design groundwater conditions;
- Use of ground treatment and its *in-situ* properties;
- Excavation width;
- Proximity to adjacent structures or utilities; and
- The use of stressed anchor systems in lieu of strutting systems.

Below is our preliminary recommended OM Application for the two ground excavation categories outlined above. This would need to be tested on projects before it could be used more widely.

OM Methodology – Excavation Category α (Soft Soils)

Excavation Category α	**Site Conditions**		
	Ground bearing structures within 10m of the excavation (see Note 1)	**Ground bearing structures < 20m from the excavation** (see Note 1)	**No Ground bearing structures within 20m of the excavation** (see Notes 2 and 3)
Case i (See Note 4)	No OM	Approach C	Approach B
Case ii (See Note 5)	Approach C	Approach C	Approach A
Case iii (see Note 6)	Approach C	Approach B	Approach A
Case iv (see Note 6)	Approach B	Approach B	Approach A

Notes:

1. For all of these site conditions a robust approach to groundwater control and monitoring is necessary, irrespective of the applicability of the OM.

2. This assumes any structure within 20m of the excavation to be piled to a stiff stratum. As part of the OM process in this case it may be possible to consider actual groundwater conditions during construction as the temporary load for impact assessment.

3. Where there are no structures within 20m of an excavation, the authors would recommend Approach A is considered, except for 'floating' excavations in soft soils.

4. The system performance in this case will be very dependent on the ground treatment performance and as such if the OM is pursued its behaviour and extent must be confirmed.

5. The OM recommendations for this case assume that all retaining wall elements extend to a stiff stratum.

6. There may be opportunities to use 'most probable' ground treatment parameters to optimize the design in these cases.

OM Methodology – Excavation Category β (Stiff Soils)

Excavation Category β	**Site Conditions**		
	Ground bearing structures within 10m of the excavation (see Note 1)	**Ground bearing structures < 20m from the excavation (see Note 1)**	**No Ground bearing structures are within 20m of the excavation (see Notes 2 and 3)**
Case i	Approach B	Approach B	Approach A
Case ii	Approach B	Approach A	Approach A
Case iii	Approach B	Approach A	Approach A

6 SUMMARY AND CONCUSIONS

The Observational Method (OM) offers very significant potential savings in construction programme and material costs as well as a rigorous and clear allocation and treatment of risk in a robust and planned way with improved safety management outcomes. The new CIRIA C760 framework presented in this paper provides clear unambiguous guidance on the implementation of the OM that is compliant with Eurocodes and international best practice which can be incorporated into any contractual arrangement. In this regard, the particular regulatory system that applies in Singapore is discussed and preliminary recommendations are made as to how the OM can be implemented on future projects in Singapore to realise the many benefits the OM has to offer.

It is hoped that by illustrating the successful application of the new C760 OM framework to major projects predominantly in the UK and Singapore via the case histories referred to in this paper, it will encourage its greater use on future projects in Singapore (and elsewhere) for the wider benefit of the projects to which it is applied and the parties involved in those projects, thereby also assisting in the advancement of the profession.

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