UNIVERSITY OF CAMBRIDGE
Centre for Digital Built Britain

# 2017/18 Mini-Project

# Adaptive design of supported excavations

# Final Report

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# Abstract

The observational method (OM) is included as a design option both in EC7 and the CIRIA 760 guide. The OM is most often invoked during construction as a 'best way out' process to optimise the design or mitigate impacts when the wall monitoring shows triggers are exceeded. Rapid redesign is then required to provide new construction plans. The newest version of CIRIA 760 clearly outlines a process for using the OM from the start as a pro-active measure allowing greater savings in materials and programme by reducing the excessive conservatism of the initial design as construction progresses. The approach is seldom used in practice due to barriers in contractual design, monitoring, construction management (risk control, time and cost) and training.

A workshop on 'The observational method for supported excavations: research challenges for removing barriers' was held in Cambridge on March 28, 2018 to identify major challenges to the practical application of the OM. A total of 28 invited participants were selected to represent as widely as possible all the expertise and functions that interact on large excavation projects: designers, contractors, and project owners.

A number of common themes emerged from the workshop discussions on barriers to the implementation of the OM:

i. Monitoring: instrumentation and monitoring planning; types and accuracy of instruments; interpretation and quality of data; sharing, transferring and preserving information.
ii. Demonstrating benefits: successful case histories, client education
iii. Contractual relations: sharing responsibilities, risks and seamless cooperation.
iv. Modelling tools: availability, transparency, accuracy

Future work will focus on developing a research programme that is truly relevant to industry and can provide the right tools for growth and innovation.

# Research Question

The observational method (OM), which was originally proposed by Peck in 1969, and formalised in Eurocode 7 in 1987, provides a way to formally reduce redundancy in excavation design and deliver projects more economically and efficiently through modifications to the original design during construction. Quite often supported excavations are over-designed and it is not unusual for measured deformations to reach values much lower than the predicted amounts. This clearly underscores a substantial potential for savings. However, the uncertainties still associated with ground investigations and numerical modelling do not allow for leaner designs at the start of the project without tight controls during construction. The emergence of advanced analysis tools, together with large amount of data now readily available during construction, make possible the development of a robust framework for a real-time and data-driven decision-making process based on the observational method, in which data can be best utilised to deliver real value, confidence, and control.

Back analysis has been applied successfully in the decision-making process for Crossrail projects, such as Tottenham Court Road Western Ticket Hall and Liverpool Street Station Moorgate Shaft. By removing a portion of the temporary retaining structures, significant savings of materials and time were achieved in both cases (Farooq et al., 2015; Yeow et al., 2014). Moreover, the lessons learned from the successful application of the OM in Crossrail projects can be used to design other excavations in the future, such as those in Crossrail 2 and High Speed 2 (Farooq et al., 2015). However, the back analysis applied in the current practice is a time-consuming 'trial and error' process, which relies heavily on engineering experience to produce the best match with the observations. The outcome might lead to biased results and does not capture the underlying uncertainties both in soil parameters and measurements.

With the emergence of advanced analysis tools and new technologies, it is becoming increasingly easier to move into a new era of excavation design by using OM-based data-driven decision making, in which the data acquired during construction can be best utilised to deliver real value, confidence, and control. However, in order to be able to support adaptive design in practice during construction, factors such as logistics, construction schedule, and risk need to be integrated into the model to ensure an optimal design in terms of safety, costs, and executability. Furthermore, technological development alone is not going to be sufficient to promote the adoption of adaptive design in construction of supported excavations. Broader changes to contractual arrangements are also needed to transform current, and well consolidated, practice.

# Methodology

This project aims to:

1. investigate barriers to the adoption of data-driven adaptive design in practice through a targeted workshop;
2. provide guidance on future research developments needed to promote data-driven design in practice;
3. promote provisions on adaptive design to be included in standards and guidance documents;
4. fully document and make available the automated back analysis tool developed by Ms Jin to support commercial implementation.

# Workshop

## The observational method for supported excavations: research challenges for removing barriers.

A workshop was held on 28th March 2018 at the Department of Engineering, University of Cambridge, to identify major challenges to the practical application of the OM in order to define research questions that would support industry in overcoming these barriers. In particular, the emphasis was in identifying opportunities that can be addressed by a partnership between industry and academia and to eventually propose a few specific initiatives to be actively pursued. The information will be used as the basis to develop a research programme that is truly relevant to industry and can provide the right tools for growth and innovation.

A total of 28 invited participants were selected to represent as widely as possible all the expertise and functions that interact on large excavation projects: designers, contractors, and project owners.

The workshop focussed on four aspects:

1. Project interactions: client-design-construction.
2. Monitoring for the OM.
3. Numerical back analysis.
4. Project controls: real time back analysis and statistical approaches.

Each session consisted of a short introductory presentation by one of the participants, followed by round-table discussions in small groups.

## Session 1- The observational method: general perspective

In the application of the OM, the construction data are continuously being assessed during the process, and used to ensure the system robustness or to optimise the current design to achieve a better economic outcome. The decision is made based on the review, and the prepared contingency plans are implemented based on the decision. Figure 2 presents the OM process defined in CIRIA report 185 (Nicholson et al., 1999).

Stuart Hardy (Arup) introduced four specific approaches in the newest OM framework, which were developed based on the timing of the decision to adopt the OM and level of conservatism. Those approaches include: the ab initio optimistically proactive, the ab initio cautiously proactive, ipso tempore proactive to make modifications, and ipso tempore reactive to make corrections (Hardy et al., 2017). Hardy presented case histories in which the OM was successfully applied thanks to improved instrumentation and site control. However, barriers still exist in many aspects of the implementation of the OM, including: bidding on a fixed price, needing tighter collaboration and integration, developing a better understanding the of OM processes through the whole team, and automating back analysis.

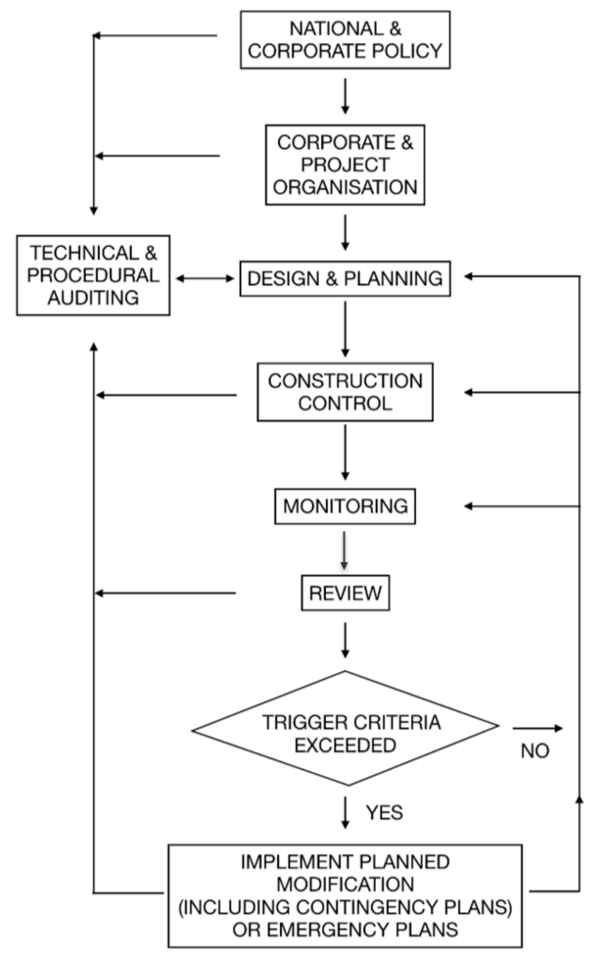

Figure 2 Process of the observational method (Nicholson et al., 1999).

Following Hardy's introductory talk, the barriers and opportunities for implementing OM in practice were discussed separately by the 5 groups. The following points summarise the notes from the discussion:

**a. Contractual issues**

One of the major obstacles to the application of the OM in practice is frequently identified in the contractual agreements among all the main parties (client, designer and contractor). The issue is how to distribute both risks and benefits in a good balance, so all would share savings as well as potential cost overruns.

The OM also requires the dynamics among the parties to change as the design-construction interactions transition from a linear to a circular process. The project team needs to be fully integrated throughout the process with designers, site managers and additional specialist contractors coordinating the review tasks, as well as the decision-making. Contractually, this requires a different approach to ensure appropriate remuneration, as well as clear responsibilities and decision processes.

Although the CIRIA guide and Eurocode EC7 both allow OM as a design approach, it is difficult for clients to embrace this change without more substantial regulatory guidance.

**b. Demonstrating savings and educating clients**

To promote OM in practice, we need to raise awareness of benefits and focus more on disseminating results from actual projects and good practices. It is essential to educate clients with case histories, in which the OM was successfully applied, and to show them the benefits in cost and program. However, many of the case histories are not available in the public domain, or the information is very limited and outdated, reducing the potential usefulness. More published information, especially of ab initio examples, and a common database are needed for different locations and geological contexts. This also raises questions on the treatment of data, both practically in terms of common standard formatting and ownership, as well as long-term maintenance.

**c. Uncertainty**

The OM is (unfairly) perceived as less safe than conventional design, therefore, risk assessment and risk management need to be detailed and fully understood by all parties in terms of design and construction. It is also crucial to make sure that the responsibilities and the roles of each of the parties in implementing the alternative designs are clearly defined.

**d. Construction scheduling**

The application of the OM as a design technique corresponds to the ab initio approach advocated by Hardy et al. (2017), in which a contingency plan may be invoked if triggers are exceeded. The transition between ab initio design to characteristic contingency plan, depends on the monitoring information and the decision-making process. This continuous process of evaluation requires additional time for assessment, back analysis, and possibly new updated predictions. These assessments need to be properly accounted for in the scheduling process, together with any impacts on timing due to changes in the procurement or specification processes. To achieve overall savings in the project, it is necessary to perform a 'business case' type of assessment for each alternative plan.

In addition, the application of the OM needs a team with the flexibility to handle changes and constant re-evaluation of design, work schedule and construction processes.

During the construction, it is also crucial to have close management cooperation amongst the whole project team, including the designer, contractor and client, to ensure the implementation of the alternative design. Therefore, an effective construction management system needs to be developed in order to ensure each process is allocated to the right person at the right time.

e. **Monitoring system**

The monitoring system is a critical component of the OM. Its reliability primarily determines the quality of the data used in the back analysis and therefore affects the robustness of the decision-making. The following considerations emerged from the discussion: 1) monitoring plans should be designed specifically and explicitly to fit OM objectives, including type and location of instrumentation and measurement frequency; 2) all parties need to agree on specifications to ensure correct implementation; 3) visualization techniques are required to provide data in a more readable form, which helps engineer assess the information in real time. Simple and easy to read graphical outputs are essential for informed decisions.

f. **Automation**

A reliable decision-making process depends on both good data and robust tools. Decisions are usually made based on back analysis, which is currently a manual model calibration process to produce the best match between predictions and available observations of ground movements. This relies on individual experience and does not characterize what constitutes the best match or how likely the predicted ground movements are to occur in the future. A rigorous approach and standardized guidance are needed to obtain parameters for most probable design and provide confidence by quantifying uncertainties.

## Session 2- Monitoring for the OM

The purpose of the monitoring in the OM is not only to verify that the structures are behaving as expected, but also to provide information for proactive adaptive design. Monitoring is, therefore, a critical component in a successful implementation of the OM. Andrew Ridley (Geotechnical Observations Ltd.) introduced the second workshop session.

The main points from the discussion are summarised below.

a. **Cooperation and data sharing**

Cooperation and collaboration on monitoring and instrumentation should start at the beginning of the project to ensure the most cost-effective and efficient system is put in place.

It is also important that the project team is fully and collectively invested in ensuring the integrity of the instrumentation and monitoring (I&M) system, as well as the overall quality of the data and interpretation.

b. **Guidance on specifications**

More targeted guidance is needed on the characteristics of instruments and monitoring procedures that best support the implementation of the OM. The instrumentation plan should be bespoke for each project, targeting specific design and construction needs with clear goals. Specifications for the number, type, quality and location of the instrumentation should be developed based on clear goals, considering a sufficient amount of redundancy. Clear guidelines linking characteristics of the I&M plan to the OM needs is highly desirable. Better understanding of the quality of instrumentation and its performance should be related to the expectations from the design and construction teams for the effective use of the information in the back analysis and decision-making process. Ultimately, the goal is for the project to select the right instrumentation for the purpose with full understanding of its limitations and have a clear cost-benefit assessment.

A common set of standards and metadata formats needs to be agreed upon in order to allow seamless integration of data into cross-validation and visualisation tools. It is important to develop guidance on data handover and storage, both short- and long-term.

Including a critical review of instrumentation and monitoring plans in the database of case histories is critical to facilitate the application of the OM in practice.

c. **Quality of data**

Quality of data is critical to the success of the OM. An accreditation procedure for instrumentation and monitoring contractors would provide assurances on the quality of their work and recognition of the importance of their role.

Specifications for the instrumentation and monitoring plan will need to be carefully written and detailed. Correct installation is fundamental for the reliability and quality of the results. Responsibilities for the protection and (short- and long-term) maintenance of the instrumentation need to be clarified.

It is also crucial to ensure that the data is collected and stored without loss or mistakes. In the current practice, many errors are caused by human factors, such as biased reading. It would be beneficial to develop a data processing and collecting system with the minimum interference from individual users.

Data should be clearly associated with detailed construction schedule information to be able to track effects of activities on the structures and the ground.

d. **New or improved instrumentation**

Long-term performance of all instrumentation is an issue. Currently, instruments are just meant to last until the end of construction, but information on long-term performance of structures could lead to important changes in the design methodology.

Reliability of piezometer data is still a major issue for the assessment of excess pore pressures, especially the negative values associated with heave in excavations.

New techniques, such as improved geophysical methods for measuring the behaviour of stiff clay, are desirable, since the measurements are required to be more accurate for back analysis than for the conventional passive checking.

## Session 3- Methods and processes for back analysis

In current practice, back analysis is mainly conducted by manually tuning the parameters of a geotechnical model to produce the best match with observations. Ying Chen (Cambridge University) presented the back analysis of Crossrail (Tottenham Court Road-Western Ticket Hall) case history carried out using three numerical approaches: FREW, PLAXIS 2D, and LS-Dyna 3D. The selection of an appropriate soil constitutive model and a level of complexity (2D, 3D) consistent with the quality and spatial distribution of the data is of paramount importance, but relies heavily on engineering experience. The number of parameters in finite element analysis can be quite large, which brings significantly increased complexity in the manual adjustment process to best match the data. At the same time, bias might be introduced in the model when personal judgement is used in the selection of the 'optimal' parameter. In addition, she noted that criteria to ensure robust convergence for the back analysis needs to be developed in a standardised way.

### a. Tools and training

One of the first questions raised during the discussion was centred on the level of complexity needed for back analysis to fully capture the relevant features of the response: if an empirical or relatively simple soil constitutive model give a sufficient answer, why use a more complex numerical model? In order to develop the right tool, it is important to evaluate the point at which model complexity stops providing meaningful improvements to the decision-making process in the OM. It also seems the complexity of the model may not necessarily enhance the confidence on decisions, whereas simplicity may facilitate understanding and more transparent decisions. On the other hand, accuracy of the predictions is clearly of critical importance. Therefore, the barrier to a more informed decision-making process seems to be related to the ability of engineers to fully understand the numerical techniques because of opaqueness in the parameter selection process of complex models and in the implementation in commercially available software. This potentially creates distrust in the results, leading to less confidence in the outcomes. More accessible training programmes, especially for less experienced engineers, are needed to ensure the correct and satisfactory use of the numerical tools.

It is critical to understand what actual features need to be fully captured by the model in order to describe the processes with sufficient accuracy. Most analysis are conducted using 2D simplifications, but the measurements are always affected by the 3D nature of the actual excavation, whether it is the final geometry of the walls or the transient earth moving sweeping across the site.

There are also considerable costs related to complex numerical analyses, both in terms of time and resources required, which may impact the schedule of the on-going project, when the back analysis is taking place during construction and the future schedule is predicated on its outcome.

### b. Data selection and quality

A second critical aspect in back analysis is choosing the right data and understanding the impact of construction activities, such as grouting, on the measurements. Selection of data for the comparison between ground behaviour and model output is not trivial: numerical analysis drastically simplifies construction activities, so measured response needs to be assessed carefully for temporary or fluctuating influences (temperature effects, for example). Therefore, measurements should be closely related to construction activities to help choose the right data at the right time. Nowadays, sensing techniques can provide a systematic way to record the construction activities and potentially can be integrated into the decision-making system.

The role of site investigation (SI) and how to incorporate the information from laboratory testing also needs scrutinising. The quality of SI results is sometimes questionable and the disconnect between the selection process for model parameters and laboratory test results can impact back analysis quite severely, and negatively. More robust parameter selection procedures from field and laboratory data would greatly facilitate the application of the OM.

An additional question is whether the right SI techniques are being employed to assess the parameters that are most critical to the accurate description of the problem. The stiffness of the soil, the structure and its components dominate the problem; however, current SI does not target these properties directly in most cases. The best technique to make this assessment is still uncertain.

Real time analysis of the data through back analysis requires careful modelling of all aspects, some relatively minute. The most meaningful time interval to approximate ‘real-time’ in analysing a range of relevant problems has also not been assessed.

c. **Experience and case history**
Since the choice of constitutive models and parameters to be updated is mainly based on engineering experience, more well-documented case histories covering a variety of wall and excavation types, as well as geologies, will provide more confidence in the tools and processes of back analysis. More published examples summarizing the correct selection and use of existing models, their area of application and limitations will also be very useful.

d. **Sharing and time commitment**
As with other parts of the discussion, the fragmentation of the design and construction processes is also reflected in this aspect of the OM. In order for the back analysis to be successful, all parties need to agree on sharing data and schedules, as well as to invest time and resources in the review process.

## Session 4- Project control: real time back analysis and statistical approaches

Automated back analysis can be used to create a rigorous process of decision-making in the OM. Different approaches using advanced data analytics tools can be used.

Antonio Canavate Grimal (Arup) introduced a range of issues/thoughts related to probabilistic analysis in the context of the OM, while Yingyan Jin (Cambridge University) presented an application of Bayesian inference to Crossrail case histories. At each stage, soil parameters are updated based on the observed data and used to predict ground movements in later stages. The Bayesian method assists decision making in OM in the following aspects: 1) the statistical approach produces a set of ‘most probable’ parameters that provides an unbiased estimate of ground movement most likely to occur; 2) the randomness in parameters is accounted for explicitly, and confidence intervals can be drawn around mean values of the updated parameters and the predictive estimation of ground movements; 3) the Bayesian method can logically incorporate all sources of information, including prior knowledge obtained from expert experience and site investigation.

a. **Data**
Machine learning techniques, of which automated back analysis is part, need accurate, good quality data to produce reliable results. Although measurement errors and systematic errors can be characterised probabilistically, other human errors in collecting and processing the data cannot be fully included in the model. However, the bias generated by human factors may significantly affect model performance.

b. **Computational costs**
Computational costs for machine learning processes are usually higher than in traditional back analysis. Most civil design and construction companies do not have easy access to more powerful computational resources that are available to research institutions. Practical applications may therefore be predicated on the ability to access these resources to demonstrate benefits in terms of cost and schedule.

c. **Statistical parameter characterization**
In addition to machine learning techniques, it is possible to assess soil parameters statistically in relevant ground conditions, if sufficient information is available. A location such as greater London is a prime candidate for the creation of a database for statistical analysis.

d. **Black-box**
Machine learning and probabilistic or statistical approaches require an additional level of expertise. As discussed previously in relation to numerical analysis, complexity can mask potential errors due to misunderstandings on the methods and opaqueness of the tools. Engineers are clearly diffident about using techniques that they do not understand well and are not able to assess in a transparent way. More training will be needed to provide a sufficient level of confidence in the quality of the results.

# Discussion

The workshop on 'The observational method for supported excavations: research challenges for removing barriers' was held in Cambridge on March 28, 2018 to identify major challenges to the practical application of the OM. The main goal was to define research questions that would support industry in overcoming these barriers and provide the right tools for growth and innovation.

A total of 28 invited participants were selected to represent as widely as possible all the expertise and functions that interact on large excavation projects: designers, contractors, and project owners.

The workshop discussions were summarised in the previous sections. A number of common themes could be identified across the discussions on barriers to the implementation of the OM:

i. Monitoring: instrumentation and monitoring planning; types and accuracy of instruments; interpretation and quality of data; sharing, transferring and preserving information.
ii. Demonstrating benefits: successful case histories, client education
iii. Contractual relations: sharing responsibilities, risks and seamless cooperation.
iv. Modelling tools: availability, transparency, accuracy

The following activities are proposed to help in supporting practical implementation of the OM:

i. Publish and disseminate widely a convincing set of case histories clearly illustrating savings in costs and schedule, as well best practices, to ensure productive interactions of all parties involved. The case histories should consider a variety of geologies, excavation methods, and support systems.
ii. Establish information needed for the implementation of the OM, tools that are most effective for back analysis, and truly effective on-site practices.
iii. Publish guidelines on the most effective approaches to instrumentation and monitoring, clearly outlining advantages, disadvantages, technical specifications of instruments. Sample monitoring plans should be developed to suit a number of different excavation types and project scales, illustrating best practices and challenges.
iv. Develop standards on data collection and sharing, i.e., recommended data formats and meta-data information labels, data storage and long-term preservation, as well as security.
v. Develop tools to capture information from different sources and of different types in one common database: monitoring data and construction progress should be linked and stored together. Ideally, the data should be updated through the life of the structure.

vi. Develop visualisation tools that can easily combine monitoring data and automated back analysis to provide a more intuitive way for engineers to interact with large amounts of complex information.

vii. Provide guidance and/or training on numerical methods for back analysis that addresses challenges in capturing soil behaviour (constitutive modelling) and problem response (type and complexity of analysis) specifically aimed at practicing engineers and application to excavations. Actual case histories should be used to illustrate relevant issues.

viii. Engage a diverse group to explore possible contractual agreements or project organisation to ensure maximum freedom to adopt the OM ab initio process.

ix. Develop more robust tools for automated back-analysis through machine learning techniques, incorporating probabilistic approaches. This new development should include further analysis to quantify cost, impact on schedule and logistics, and risks of every possible alternative design. The construction management analysis can be integrated into the automated back analysis so that the whole decision-making process can be fully supported.

## Conclusions

The workshop on ‘The Observational Method for supported excavations: research challenges for removing barriers’ provided a number of paths forward for activities which will help in making the OM more attractive from the start of the project. Some of these proposals will require a broad collaboration from industrial partners to share information and best-practices. The enthusiasm demonstrated by the workshop participants indicates there is quite a lot of interest in moving forward on this. After circulating the report on the workshop outcomes we will engage with the industrial partners to develop a plan for future work and strategies for engagement of relevant academic partners, industrial sponsors and agencies.

## Additional Accomplishments

Funding from the mini-projects award from the Centre for Digital Built Britain partially supported work on publications to provide guidance on the application of the observational method in practice and documentation on effective machine learning techniques for the implementation of adaptive design:

Hardy, S., Nicholson, D.P., Ingram, P., Gaba, A., Chen, Y. *, and Biscontin, G. “New observational method framework for application to embedded walls,” submitted to *Geotechnical Research* in March 2018.

Jin*, Y, Biscontin, G., and Gardoni, P. “A Bayesian definition of ‘most probable’ parameters,” submitted to *Geotechnical Research* in May 2018.

Both papers acknowledge support from CDBB.

The draft of a paper on monitoring and instrumentation for the implementation of the observational method is in progress. Tentative title: ‘Specifications for instrumentation and monitoring plans for supported excavations.’ We also have a preliminary agreement for a white paper on this topic with the Centre for Smart Infrastructure and Construction (CSIC).

Drafts of journal publications on Dr Jin’s thesis on machine learning techniques applied to the back analysis of deep excavations are in development. As part of this process Dr Jin is writing a guide to the implementation of her algorithms for the distribution to software developers. We received some inquiries from software developers interested in the application.

## Related and Further Work

Dr Jin developed the building blocks of an intelligent self-updating excavation information system, which could be extended to other underground construction, and further upgraded with the integration of analysis to quantify cost, impact on schedule and logistics, and risks of alternative designs. The tool could be extended to integrate automated data acquisition systems, such as remote instrumentation feeding in measurements and sensing techniques that record construction activities. The integration of heterogeneous data including geology conditions, design information, construction activities, monitoring data, image records, and numerical predictions can be provided in real time to facilitate decision-making. All this can potentially be achieve within a Building Information System (BIM) framework for underground construction.

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