DEEP EXCAVATION IN HONG KONG –
DESIGN AND CONSTRUCTION CONTROL

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Abstract: This paper is presented in three parts. The first part discusses the design of deep excavations including limit states, partial safety factors and ease of construction. The second part discusses recent trends in numerical analysis with particular emphasis on reliable displacement prediction while maintaining control over the input parameters. The third part discusses the potential benefit of using the observational method and discusses how the benefits of this method can be employed in the highly regulated regime that operates within Hong Kong. A common theme in throughout this paper is the successful application of design and construction methods that maximize economy while ensuring safety.

INTRODUCTION
Due to the shortage and therefore high cost of land in Hong Kong the use of deep excavations has been widespread for over 30 years. While their design and construction has generally been successful there have been some notable failures (GEO 2002). It is clearly important that the design process meets the proper balance between safety and economy. The design process must understand what may go wrong and that the effects on neighbouring buildings and structures are adequately predicted.

This paper presents an overview of current and developing practice of the design of deep excavations in Hong Kong. It is in three parts and addresses the following aspects
\begin{itemize}
  \item Design considerations.
  \item Numerical modelling.
  \item The observational method.
\end{itemize}

PART 1: DESIGN CONSIDERATIONS
It is important that the design process for deep excavations results in a structure that is as economic as possible but at the same meets its performance objectives. These objectives will usually include providing safety to the workers involved in the construction as well as the nearby public and limiting movement experienced by neighbouring structures to tolerable levels. The Limit State design method directly addresses these type of issues and formalises the procedure of identifying the various ways in which the structure may not perform and direct the designer to show that they will be avoided. In the design process normally both ultimate limit states, which explore ways in which the retaining wall and associated propping may become unstable and ensuring they will not happen, and serviceability limit states, where the expected movement of the surrounding ground is assessed and shown to be tolerable to nearby structures, are addressed.
Hong Kong design practice

Until recently in Hong Kong, the ultimate limit state consideration of stability of the retaining structure for an excavation was carried out using a global factor of approach as described in GCO Publication No. 1/90. In 1993 the GEO published the second edition of Geoguide 1 “Guide to retaining wall design” and this document introduced the concept of partial safety factors. Partial factors were recommended for soil strength and for applied surcharges. The scope of that report was limited to gravity retaining walls and not for deep excavations. In 2003 the CIRIA Report No. C580 entitled “Embedded retaining walls – guidance for economic design” was published. It advocates partial safety factors for ultimate limit state stability checks and gives guidance on expected movements and analyses methods for serviceability limit state checks. For the ultimate limit state stability checks it advocates that soil structure interaction computer analyses be used rather than simple limit equilibrium methods. These analysis methods may include beam on springs methods, boundary element methods such as FREW (Pappin et al 1986) or two dimensional (2-D) [or 3-D if appropriate] finite element methods. As part of the ultimate limit state design checks it has the additional requirement that the wall element and the propping support systems are able to resist the forces applied to them as calculated when using the factored soil strengths. If serviceability limit states are also relevant then the structural elements must also be able to resist the induced forces when considered as working loads. The ultimate forces therefore applied to the structural elements are the envelope of the forces from the serviceability limit states factored up by about 1.4 and the forces from the ultimate limit states. About 1 year ago the GEO recommended that the design methods in CIRIA C580 be allowed in Hong Kong provided that the partial factors as stated in Geoguide 1 are adopted.

Partial factors and design reliability

It must be emphasised that a more consistent reliability of the safety of a design should be achieved if partial factors of safety are used. Applying a margin of safety directly onto soil strength is the same process as that conventionally used in slope stability analysis and will give a relatively reliable margin of safety unless the strength of the soil at the site in question is either not well known or has an unusual variability. Generally a partial factor of safety on the drained soil strength will give a consistent margin of safety for most soil types. Moderately weathered residual soil can be difficult to interpret and a conservative lower bound value of strength will probably need to be assigned unless extensive data exists. For a deep excavation where there is soft marine clay under recent fill, particular care is required to ensure the stratigraphy and undrained strength of the clay is adequately understood. It is tempting to characterise the clay material as being drained and using drained strength parameters but this is not a conservative assumption especially when assessing the passive resistance provided by the soft clay beneath the excavation.

Ground water effects

CIRIA C580 gives systematic guidance to determine the toe level of the retaining wall. It must be noted however that, while it can be demonstrated that very short toe penetration can still be shown to be stable, the propping forces and bending moments imposed on to the retaining wall can become very large and therefore a less economic wall be designed (see Sze and Lo, 2005). Another, potentially more serious problem with small toe penetration, is the loss of passive resistance in front of the retaining wall due to excessive pore water pressure leading to a reduced effective stress in the soil beneath the excavation surface. On a recent project in Hong Kong this problem was eliminated by inserting passive drainage wells at about 10m centres in front of the toe of the diaphragm wall as shown in Figure 1. This
method allowed the wall toe to be kept as high as possible while at the same time ensuring hydraulic stability.

![Schematic Diagram showing location of passive wells](image)

**Figure 1: Schematic Diagram showing location of passive wells**

**Ensuring Buildability**

The review of past cases of failures and excessive displacements of deep excavations in Hong Kong (GEO 2002) showed that most problems have arisen because of inadequate sheet pile penetration or because of removal of some (or even all) of the temporary props supporting the wall. In many cases this was the result of the design being difficult to construct. While it is clear that having a sheet pile retaining wall penetrating into very strong material is good from a toe stability perspective it is not a good design if it is virtually impossible to achieve this penetration. Admittedly the penetration could probably be achieved with pre-boring but this expensive procedure needs to be specified and costed into the project at the time of tender if the contractor is to be realistically expected to carry out it out on any but a very minor scale.

Many levels of propping are also shown to be a potential problem. While using multiple levels of propping at close vertical centres of 2m or so will reduce the lateral displacement of the wall it causes major problems to the excavation contractor as he attempts to fit plant and machinery within the props when removing the material from the base of the excavation. Inevitably the contractor will tend to over-excavate and even temporarily remove props to be able to manoeuvre his equipment. Experience has shown that the use of more substantial and more widely spaced props provides a more workable and therefore safer solution. In certain circumstances where a TBM is to be launched from within the deep excavation a clear working height of over 10m may be necessary and diaphragm wall combined with a propping spacing of the order of 5 to 6m has been found to be effective. Top down excavations, where the propping is provided by the permanent floor slabs, also prove to be effective in this regard.
PART 2: NUMERICAL MODELLING

Numerical modelling of horizontal deflection of retaining walls has been in use for nearly 30 years. As early as 1976, simple computer programs representing a wall as a “Beam on springs” have been used in Hong Kong. For example, close comparison was found between predicted and observed deflections of a wall panel at Choi Hung Station, (Endicott 1980). These programs did not compute settlements outside the excavation. Where settlement was of concern, empirical relationships between settlement and depth of excavation were commonly adopted, (GCO 1982, and Endicott and Cheung, 1991).

The computer programs could also be used for back analysis of field results and it was quite usual to find that the stiffness of the ground was significantly greater, say 3 to 9 times greater, than measurements on small test specimens, (Endicott 1984).

In the mid 1980’s computer programs were made generally available on a commercial basis and continuum models incorporating 2-D finite element or finite difference methods provided the opportunity to model ground movements generally. For example, FLAC, (ITASCA 1987), has been used for retaining wall design in Hong Kong, since 1986, (Endicott and Cheung 1991).

It was found that predictions of ground movement based on simple models with linear elastic/plastic solutions, when compared with field monitoring, show that predicted settlement is affected by the width of the numerical model. This effect can be overcome. When soil stiffness is varied, high stiffness for small strains and small stiffness for large strains, a closer match is obtained. The effect can be achieved by using sophisticated constitutive models such as “Bricks on strings” (Simpson 1992), although such models are tools for specialists. For practical purposes there is a simple approximation for retaining walls. One can manually assign high stiffness at a distance from the wall where the strains are small and small stiffness close to the wall. By this means one can closely model behaviour observed in the field.

In practice, deep excavations are seldom carried out in 2-D. Usually there are other factors such as staged construction, or the excavations are of limited length. Many basements are nearly square in plan. These effects are likely to restrain movements to less than those obtained when using basic parameters and 2-D analysis. Likewise back analysis of monitored movements using 2-D analyses result in pseudo parameters, i.e. parameters for use with 2-D analyses for excavations with end effects, and not fundamental soil parameters.

Currently, 3-D codes are available and desk top processors are increasingly powerful with growing memory size. As a consequence 3-D analyses are coming into use for current projects.

Tsim Sha Tsui Station Concourse Extension

In order to illustrate current practices of applications of numerical modelling for deep excavations in Hong Kong, a case history is presented below.

Tsim Sha Tsui Station is one of the first underground stations in Hong Kong and was opened in 1979. Ongoing improvements to the system in 2002 included a requirement for increased entrance capacity of Tsim Sha Tsui Station. It was proposed to extend the concourse southwards by cut and cover construction over the existing running tunnels. The work involved removing 9m to 10m of overburden leaving only 1.5 m of cover over twin bored...
tunnels in soil. Figure 2 shows a site plan and a typical cross section illustrating the ground conditions at the site is shown in Figure 3.

Figure 2: Layout plan showing the extension to the Tsim Sha Tsui Station concourse constructed below busy Nathan Road

Figure 3: Typical cross section showing the ground conditions and the proposed works
The vicinity of the station is intensively developed with buildings of the order of 17 storeys high, founded on driven piles. Some of the piling is quite old and of uncertain capacity. The issues were, how much would the adjacent buildings settle, how much would the diaphragm walls move together and compress the running tunnels and how much would the tunnels rise due to the removal of overburden. It is a requirement that MTRC structures shall not be displaced by more than 20mm (Building Authority PNAP85: 1981).

The project was an unusual one. Therefore one could not rely on previous experience and the project would have to be designed from first principles. It was complex because of the configuration and phasing. At the planning stage, a trial analysis making a simple conservative approximation and using 2-D analysis predicted that removal of overburden would result in a rise of the tunnel crown of the order of 35mm, well in excess of the limit of 20mm. Additional measures, such as extensive ground improvement would have been uneconomical. Therefore a preliminary design was carried out taking account of the phasing and 3-D effects by adopting two orthogonal 2-D finite element models located longitudinally and transversely. The longitudinal model was used to derive out of plane stiffness to add to the transverse model to represent longitudinal effects. Coupling the interaction between the models was carried out by manual iteration. This showed that predicted movements would be reduced by taking into account the sequence of construction. Subsequently a 3-D model was set up using FLAC 3D and the full sequence of construction was included.

Figure 4: View of the 3D FLAC model developed showing the lateral wall deflections along the length of the excavation
Figure 5: Plan view from the FLAC 3D model showing the displacement of the tunnel linings along the length of the excavation.

Figure 6: Wall deflections and tunnel deformations obtained from the FLAC 3D model at a section about 40 m from the southern end.

Maximum tunnel lining displacement of about 32 mm at the middle of the excavation.
Output from the analysis is shown in Figures 4 to 6 (Figure 4 shows the overall model). In particular it demonstrated that the maximum displacement at the crown of the tunnel could be about 32 mm. see Figure 5, and the maximum horizontal movement of the diaphragm wall could be limited to about 22 mm, see Figure 6. This result verified the results of the 2D analysis and added confidence in the numerical methods.

Subsequently the strutting sequence and pre-stress loads were changed and a re-analysis was carried out. As a consequence the predicted deflections were reduced compared to the preliminary design. It was able to be demonstrated that deflections could be controlled economically to within the required limits, and the project was considered feasible and could go ahead.

The results of some of the monitoring are shown in Figures 7, 8 and 9. These show that the vertical deformation (rise) of the tunnels was controlled to less than the Alert Limit of 10 mm and the inwards movements of the walls were less than 10 mm.

It may be concluded that the modelling in 3-D was sufficiently realistic. Certainly a back analysis exercise to calibrate the model by comparison with the monitoring data would validate its adoption in the future as a predictive design tool.

![Figure 7: Results of tunnel deformation monitoring using an Automatic Total Station Deformation Monitoring System inside the down-track tunnel](image-url)
Figure 8: Results of tunnel deformation monitoring using manual tape extensometers at Section D1 K at the middle of the excavation

Figure 9: Wall deflection measurements from inclinometers installed along the eastern wall extensometers at Section D1 K at the middle of the excavation
Problems With Numerical Modelling
With proper use, numerical modelling is a useful tool for the designer and for the constructor. However there are many pitfalls and mistakes are common.

Numerical modelling is often likened to use of a “Black Box”. The imagery is one of putting numbers in and getting numbers out without understanding what goes on inside. This can arise especially when a commercial program is provided with default values for input parameters. In such a case the user can achieve instant gratification, the program operates and provides an answer but the risk is that the parameters are other than those required for the design. Intelligent users can understand how a program operates but this is not easy where the code is not accessible and the user can only find out by trial and error.

Despite education and training, silly mistakes can he made. For example a variable soil profile beneath a symmetrical building was modelled using an axi-symmetrical model. The mistake was to put the axis of symmetry outside the building. Another common mistake is to forget to zero the displacements after setting up the original stress field. Including bulk excavation for the removal of a hill, the response of applying a modest load on a foundation can be output as a net rise or ground heave!

It is common to use average parameters. This yields mid range predictions, not maximum and minimum predictions. Adopting a material factor can grossly distort the results and in some programs even small changes in parameters can greatly change the results. Reliance on a one-off analysis without a parametric study or a good understanding of the program can be very risky.

Sophistication allows complex constitutive modelling and many parameters, therefore it is possible to converge to a reasonable solution as the result of compensating errors, or have an incorrect basis of design, or an incorrect understanding of key factors. Therefore there is not much chance of understanding what has happened in the field when something goes wrong. For example, the Committee of Inquiry's hearing of the collapse of the Nicoll Highway in Singapore (Singapore Government, 2005) started with several opinions that there was a soft ground base failure of a deep excavation. These opinions were widely disseminated by The Press, but they were based on computer analyses and were not consistent with site monitoring and eye witness accounts.

PART 3: THE USE OF OBSERVATIONS MADE DURING EXCAVATION
The preceding sections of this paper have described aspects of the design methodology applied to temporary lateral support for excavations and have presented observations from projects in Hong Kong of how actual performance and predicted performance compare. In this section examples are presented illustrating how design and risk evaluation based on theoretical analyses should be augmented by realistic contingency planning combined with continuous observation throughout construction as a means of improving the overall performance of the excavation.

What Constitutes a Well Performing Excavation?
Different parties may perceive performance in different ways to some extent dependent upon at what stage in the process the view is taken. At the outset, however, there are clear areas where objectives of both Client and Contractor are essentially the same. Fundamentally objectives can be divided into those aimed at personal and property protection, which we
might call Protective Factors and those aimed at avoiding unnecessary overspend on the works, in other words Commercial Factors.

**Protective Factors**
- The works should be totally safe against collapse.
- Adequate protection should be provided to nearby structures and roads etc.
- The design should make provisions to allow for a safe working environment.

**Commercial Factors**
- The system should permit reasonably rapid progress of work.
- The cost should be as low as possible after considering the above points.

The one single dominant factor which bridges the Protective and Commercial considerations is the risk arising due to uncertainty as to the actual conditions in the ground, whether it be fundamental soil characteristics, soil/rock stratification, performance of groundwater, foundation conditions of existing buildings and structures or obstructions etc.

Civil and geotechnical engineers are accustomed to putting to use the considerable reported experience and increasingly advanced analytical tools to refine designs for underground excavations. Nevertheless significant divergence of views will commonly (or invariably) arise concerning how to attain a satisfactory balance of the protective and commercial aspects of a design solution. Such divergent views may arise from many factors amongst which might be;
- preferences for different analytical tools; for example variations in design actions derived using different software for wall analysis may commonly be seen to be 10% or more,
- views on whether disturbance due to field sampling significantly affects parameters derived from lab testing,
- considerations of whether to adopt parameters based on an average of values derived from site investigation or some more or less conservative basis,
- views as to whether certain parameters may themselves change as work progresses, such as might occur as a result of gradual desiccation of soft clays in the proximity of cementitious grout.

Undoubtedly the process toward agreeing design parameters before excavations proceed is arduous and the outcome is rarely satisfactory to all parties concerned.

**The Only Sure Way is the Observational Way**
The modern observational approach to excavation is certainly not new, probably dating back 40 years or more. There are records of its use in Hong Kong, such as for the excavation for MTRC’s Tseng Kwan O Station, as reported by Pan et al (2001), where the method was used to justify the omission of a layer of props and a buried prop for sections of the work carried out at later stages of the project.

In another example of a recent project undertaken using the observational approach, it was possible to omit the lowest layer of struts where excavation was being carried out in very soft clay and where significant doubt existed initially about the potential effectiveness of a jet grouted buried strut installed before excavation commenced (see Figure 10). This particular example illustrates quite effectively how the observational method gave access to a solution which would be unattainable in any other way, i.e. sampling of the jet grouted ground before excavation commenced showed quite patchy results as to the degree of strength improvement resulting from jet grouting. Based on this sampling, it was necessary to adopt conservative
parameters for strength and stiffness of the grouted layer. The observations of strut load and wall deflection as excavation proceeded indicated that the grouted clay was performing significantly better than anticipated.

As the excavation was completed and the grouted ground exposed the reason became evident. There was a very obvious desiccating effect of the grout which had caused the untreated ground above, below and, more importantly, interspersed between grout patches to harden quite dramatically. The desiccating effect was possibly also augmented by a pozzolanic effect. Both effects would have been time dependent, hence the inability to identify the true behaviour of the grouted soil before excavation commenced.

There are few examples other than these, and it is probably true to say that use of the observational approach is still a rarity in Hong Kong.

**Why Isn’t the Observational Approach Used for Every Excavation?**

Some of the fundamental problems with observational design in the past have related to;
- time lag between making the observational measurement, reporting and interpretation,
- concerns as to reliability of reported measurements,
- the time involved in obtaining authority approvals to changes in sequence of work.

The first two points are being addressed in modern instrumentation systems such as those applied at excavations recently carried out for KCRC’s East Rail Extensions in Hong Kong. The system employed on these projects uses an internet web based reporting interface which is directly connected to automatically reporting devices such as load cells, strain gauges, piezometers and the like. Every reading taken by these instruments, whether it is hourly, daily or weekly is instantaneously uploaded to the system and available immediately for enquiry (see Figure 11 for example). The system can be set up with predefined alert and alarm limits that automatically trigger messages to relevant parties via email or via cell telephone. Time lag is therefore eliminated and the on-line reports, both current and archived, are available to all parties concerned without the possibility of manipulation thereby giving assurance as to their reliability.

The more difficult issue to address is how to retain a satisfactory level of authority control which gives the flexibility necessary for the observational approach to work. The following describes how this could be achieved whilst working within the framework of the procedures adopted for projects under the authority of the Buildings Department or other authorities such
as the railway companies.

Figure 11: Example of online report of strut load measurements, reported two hourly, showing how trends are instantly visible (equally, anomalies would be immediately evident)

The CIRIA Guide C580 (Gaba et al 2003) defines two approaches to selection of soil parameters for design as follows:

**Approach A**: Use parameters selected from a “Moderately Conservative” assessment of available field and lab measurements.

**Approach C**: Use the “Most Probable” parameters defined as those which have a 50% probability of being exceeded. These parameters are recommended only to be used in conjunction with the Observational Method.

To date, it seems, there remains a tendency still to use “Moderately Conservative” parameters even when the Observational Approach is to be used, perhaps because no clear strategy for authority control is put into place. With the strategies described in outline below it should be a straightforward matter to move on to the use of “Most Probable” values.

**An Illustration of a Design Approvals Strategy for an Observational Excavation**

Consider a deep excavation in soft ground requiring multi-layered propping. An analysis using moderately conservative geotechnical design parameters indicates that 5 levels of strutting would be required to suit the chosen type of retaining wall and taking into account what is acceptable for displacement of the wall and resulting ground movement. This design is illustrated by “Design A” in Figure 12

By using a more favourable set of parameters it is possible to show that 4 levels of strutting would be safe if soil conditions actually were to match these parameters (see “Design B” in Figure 12). The Observational Approach is to be used to substantiate that the 4 level scheme can be followed, hence in the submission made for approval it is necessary to identify a test
condition, as early as possible during the progress of the excavation, which can be used to validate the more favourable parameters.

In this case it is identified that the earliest meaningful test condition from which one could reliably conclude, based on observations of strut load and deflection, that the more favourable parameters were applicable is for excavation to a specified level below the third strut level.

Effectively two complete sets of design have been submitted and approved before commencement of the work, “Design A” and “Design B”. A test condition has been defined and approved in advance. In this case the test condition would be that observed strut loads in the first three levels and deflections were below the values predicted for “Design B”. Assuming that the test condition is satisfied the 5th level of struts could be omitted.

The most important aspect of this procedure, as illustrated in the very simple case above, is that it has been unnecessary before commencement of the excavation to prove to the approving authority that the more favourable parameters are applicable. Only the parameters adopted for “Design A” need be accepted at that stage. Whether the more favourable parameters are applicable, which might be considered a matter of conjecture before commencement of excavation, becomes a matter of fact once observations have proven the test condition to be satisfied.

The decision to follow the “Design B” route should be the responsibility of the supervising engineer, the Registered Structural or Geotechnical Engineer in the case of private building work. There would be no need for a formal hold point requiring the submission of a report to the Authority for acceptance that the test condition has been met provided that the instrumentation reporting system has be configured to provide a consistently up to date archive of all observations to the Authority.

**Further Developments for the Observational Approach**

In the foregoing, discussion is based around definitions in CIRIA C580 of “Moderately Conservative” as compared to “Most Probable” soils parameters.

Conceptually, there is no need to interpret the term “Most Probable” in the way defined in C580 as the statistical median value of parameters measured from ground investigation, as to do so may still constrain the proponent of the design to seeking consensus from all sides on what constitutes a valid measured parameter. In many circumstances the proponent (usually
the contractor) may believe it will be justifiable to adopt even more aggressive parameters than indicated by field measurements and the case quoted above of the desiccation of the soft clay due to grout hydration is a good example of this. Provided realistic contingencies are defined in advance and a robust mechanism for instrumentation, reporting, interpretation and control is in place, the protective attributes of the design will always be assured. In this way contractors can be given the flexibility to make their own decisions as to how best to control the economy of the work either through a balance of upfront investment in the lateral support system or in provisions for contingencies (both physical and time).

Equally it must be acknowledged that there will be circumstances where the observational approach must be used with more caution, for example where there are what might be termed “brittle” elements affecting the stability of the excavation such as, for example, unfavourably oriented relic joints in dense soils.

CONCLUSIONS
For the design of deep excavations the limit state design methodology combined with partial safety factors applied to soil strength is preferred to global factors of safety and will lead to a more consistently reliable and economic design.

The CIRIA C580 approach of ensuring the structural elements can withstand the ultimate limit state design checks is also recommended. Interestingly the approach can show that the most economical solution may not be that with the minimum wall toe penetration below the excavation level.

It is important that groundwater conditions in the passive zone beneath the excavation is considered and controlled especially when small toe penetrations are used.

Reviews of past failures show that most problems are caused by buildability problems being implicit in the design and this aspect needs to be addressed at an early stage of the design and construction process.

2-D finite element numerical modelling is now tried and tested and is in regular use as a design and construction management tool.

Sophisticated 3-D finite element numerical programs are available and can be used for modelling more realistic geometry and sequences of construction. However sophisticated modelling is a specialist activity and, for regular work, constitutive modelling should be kept as simple as possible.

Where time is critical, as is often the case in the private sector projects in Hong Kong, it is better to use a simplistic design, a conservative approach with prescriptive parameters. If the project is unusual and tricky and the client plans well ahead then more detailed modelling may be warranted.

There are large potential benefits from using an observational approach as the construction proceeds. This paper outlines an example procedure showing how the observational approach can be applied in the highly regulated environment of Hong Kong.
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