Uncertainties and their relevance for the design of deep excavations near existing structures.

Incertitudes et leur pertinence dans la conception des excavations profondes a proximité d'ouvrages existants.

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1 DESIGN PROCESS FOR DEEP EXCAVATIONS IN URBAN ENVIRONMENT

The design and construction of deep excavations in urban environment is often governed by deformation criteria related to risk damage to adjacent structures. Table 1 summarizes main factors influencing the movements of retaining structures and thus the behaviour of the adjacent structures or utilities.

Table 1

Category	Related factors and illustration
Support system	Earth support conditions (embedment depth)
	Flexural stiffness of wall (soldier piles, sheetpile wall, diaphragm wall and secant piles)
	Prestress and stiffness of support system (prestressed anchorages, nailing, bracing...)
	Vertical restraint of the wall
Ground properties	Shear strength and stiffness of the ground behind the wall and at the passive side
	In situ stress conditions (k_0 and OCR; previously experienced effective stresses)
	Heterogeneity of soil and spatial variability of property
Construction method	Wall installation (previous to excavation by driving, vibration, ground removal or hand over hand facings)
	Dewatering
	Excavation technique (dry or under water, depth of cantilever before first support is installed, excavation depth under support...) and support installation technique

In a very simplified way, the design process for a deep excavation nearby an existing structure or utility consists of three main stages:

1. Establishing limiting deformations for the adjacent structure and translating them into design criteria for the deep excavation and construction requirements;
2. Analysing the results of in-situ and laboratory tests and selecting parameter values for design accounting for the intended calculation models and types of retaining structures likely to be used;
3. Selecting appropriate design models and performing the calculations. Evaluating the calculation results and comparing them to the design criteria; adapting or optimising design if relevant.

The steps yield specific uncertainties which need to be evaluated carefully in order to proceed with the design-decision process, despite the remaining doubts, towards a well balanced final design and construction requirements. Some of the uncertainties will be offered for discussion through two evaluation criteria:

1. Is the reliability of the considered design stage good or, at the contrary, rather poor? (identification of the degree of uncertainty implied in the design stage being performed)
2. Is the consequence of an erroneous decision in the considered design stage relevant or for the final design? (Evaluation of consequences and dealing with the identified degree of uncertainty)

The discussion should help to detect to most relevant needs for improvement in the design process. The discussion focuses on predictive design: Active design and observational methods, which take advantage of measurements during execution to adapt the design, are not included in the present discussion, as their application remains unfortunately rather marginal in most of the deep excavations. Effects on ground movements due to poor execution (overexcavation, delays, inadequate support, face instability...) are of great importance, but are not discussed here.

2 DESIGN CRITERIA RELATED TO THE NEARBY STRUCTURE

The design criteria are established to minimize the risk of damage (structural damage, appearance...) to the adjacent structures. Potential causes of damage are often related to differential settlements of the structure affected by the deep excavation or dewatering. Damage due to vibration will not be treated further. Poulos (2001) summarised the recommendations of many authors on criteria for settlements and differential settlements of building (see table 2).

Table 2. Limiting values of settlements and differential settlements for buildings (after Poulos, 2001)

Type of structure	Type of damage/concern	Criterion	Limiting value(s)
Framed buildings and reinforced load bearing walls	Structural damage	Angular distortion	1/150-1/250
	Cracking in walls and partitions	Angular distortion	1/500 (1/1000-1/1400) for end bays
	Visual appearance	Tilt	1/300
	Connection to services	Total settlement	50-75 mm (sands) 75-135 mm (clays)
Tall buildings	Operation of lifts & elevators	Tilt after lift installation	1/1200-1/2000
Structures with unreinforced load bearing walls	Cracking by sagging // hogging	Deflection ratio L/H	L/H=1: 1/2500 // 1/5000 L/H=5: 1/1250 // 1/2500
Bridges – general	Ride quality	Total settlement	100 mm
	Structural distress	Total settlement	63 mm
	Function	Horizontal movement	38 mm
Bridges – multiple span	Structural damage	Angular distortion	1/250
Bridges – single span	Structural damage	Angular distortion	1/200

Criteria such as those summarised in table 2 are valid for settlements due the structure itself. It is questionable whether they can be used for ground movements induced by deep excavations or by ground water table lowering. Boscardin et al (1989) points out the importance of horizontal strain in initiating damage: the larger the horizontal strain, the less is the angular distortion before some form of damage occurs. The table 3 gives indicative values for the admissible mean value of the surface settlements related to structural damage due lowering of the phreatic ground water table according to the Dutch practice. More severe value may be required for old or historical buildings and less severe values may be admitted for modern RC buildings on good foundations or rafts.

Table 3. Value of admissible settlement due to lowering of the ground water table (Dutch Practice)

Structural state	Unfavourable factors	Neutral factors	Favourable factors
Good	17 mm	23 mm	33 mm
Mean	12 mm	17 mm	24 mm
Bad	10 mm	13 mm	20 mm

The main difficulties encountered when establishing the acceptable limits of displacements (or vibrations) for the structures affected by the excavation or dewatering are:

- The actual state of the structure is often difficult to evaluate, especially for old or historical buildings due to lack of information on their foundation and bearing structural elements, existing stresses due to previous deformations are difficult to determine...
- Usually, the vertical and/or horizontal ground movements are calculated without accounting for the stiffness of the affected structure: the calculated ground movements are supposed to be entirely transmitted to the structure in order to evaluate the potential damages. Potts et al (1996) and Mroueh et al (1998) attempted to account for relief of differential settlement due to the stiffness of the structure for tunnel-induced ground movements.
- Limiting values of deformations are related to accepted risks of damage to the structure; often owners of buildings or services are very reluctant to accept any risk of damage.

For deep excavations, the settlement criteria of the adjacent structures have to be translated to limiting displacements values of wall displacement. Usually this is done on an empirical way. Continuum models avoid the need of such translation, but the reliability of surface movements is very poor. The present practice is often that a limiting value is required for the wall displacement, without quantified relation between that limiting value and the admissible settlements of the adjacent structure. One even observes that in many designs, at an early stage of the process, definite decisions concerning e.g. the type of wall are taken by lack of capacity of establishing the right criteria. These decisions are seldom re-evaluated, and hence a complete and refined design is performed giving a solution to sometimes undue or exaggerated problems.

The table 4 propose some strategies for establishing design criteria depending on the accuracy by which they can be established (good or poor accuracy) and the consequences of the deformations (small corresponding for instance to easily reparable damage, e.g. road settlement, and important corresponding to difficult and expensive repair works, e.g. historical building).

Table 4. Possible strategies for selecting design criteria related to damage of the adjacent structure

Accuracy of	Consequences of vertical and/or horizontal displacements	
design criterion:	Small	Important
Good	Apply routine design methods	Select "mean value" criterion
Poor	Establish range of acceptable deformations and do not focus on most severe bound	Select safe criteria (e.g. lower bound of admissible deformation)

3 SELECTION OF GROUND PARAMETER VALUE

The vast problem of selection of the parameter values for displacement controlled design is widely recognized. The ground investigation and laboratory tests should be relevant for the intended construction method and calculation models; test results should be compared with published data and local experience. Main factors when analysing the results of ground investigation and selecting parameter values for the prediction of ground movements due to excavation or dewatering are:

- The heterogeneity of the subsoil under the nearby structure as well as the variations of parameter values should be identified and quantified, as the occurrence of damage is by far more governed by differential displacements than by the absolute magnitude of a mean deformation. It should be noted in this respect that the ground under the existing structures is quite impossible to explore
- The influence of initial stress conditions including the previously experienced effective stresses prior to commencement of excavation or dewatering is often underestimated. The errors involved by this can be at the side of safety as well as at the opposite site.
- Parameters for time dependent effects are difficult to obtain and to translate to reliable design parameters

The table 5 proposes a strategy for the selection of parameter values depending on the accuracy by which the parameter value is can be selected and the consequences of inaccurately selected values.

Table 5. Possible strategies for selecting design parameter values

Accuracy of knowledge of ground	Effect of uncertainty on parameter value	
parameter value and heterogeneity	Small	Large
Good		Select somewhat cautious value
Poor	Use "mean" parameter value and accept possible difference between real and predicted behaviour	Select cautious parameter value and analyse sensitivity of the design to variations of parameter value

4 DESIGN MODEL

Models for predicting displacements range from empirical methods and design charts for preliminary design (e.g. Clough,1989, 1990) to sophisticated FEM calculations. Design charts and compiled local experience are extremely valuable for preliminary design as well as for comparison with the results of more sophisticated calculations. It is commonly agreed that calculation models employing load path techniques in order to follow the installation and excavation process and simulating the interaction between the soil and the wall (e.g. subgrade models using non-linear spring and continuum models) should yield the most reliable predictions. Only continuum models allow for the calculation of ground movements behind the wall. Reliable values of predicted surface settlements appear however more difficult to obtain than for wall displacements and require the use of advanced constitutive models.

Prediction exercises and analysis of benchmark problems indicate that the accuracy of the calculation models and corresponding selection of parameter values remains a widely recognised point of concern despite the continuing improvements in soil and structural modelling. The complexity of selection of constitutive model and parameter values is a well-known factor of influence, but not the sole one. Schweiger (1998) has pointed out that for FE models, even for a very well defined benchmarking problems (without need of interpretation of ground investigation), important relative differences between different predictors are found. However, for daily design the reliability of a calculation method should not be judged on base of the relative error alone, but on the effects of the error on the risks of damage to the adjacent structure: 50 to 100 % error for a calculated wall displacement of 3 cm is not unlikely to occur, but a wall displacement of 5 cm instead of 3 cm may have no effect on the adjacent structure. Inaccuracies or theoretical shortcomings of calculation models are often compensated by cautious selection of parameter values based on experience; this probably leads "in the average" to somewhat conservative designs.

Table 5. Possible strategies for selecting calculation models

Expected reliability of the calculation, (including parameter value selection)	Consequence of unaccurate calculation results: Small	Consequence of unaccurate calculation results: Large
Good		Apply model
Poor	Avoid spending too much time to the calculation	Avoid use of model or improve check for worst case scenario

5 TOPICS PROPOSED FOR DISCUSSION

This brief, thus incomplete, review on the design for deep excavations nearby adjacent structures leads to several topics for discussion of which some are listed below:

- Which uncertainties in the design process do affect the design in the most significant manner?
- Is it possible to remove or to reduce dominant uncertainties in a simple way for practical design problems, or is there a need to accept them and to develop strategies to evaluate and to mitigate their effects?
- Is there a need to refine the design criteria related to avoiding damage to the adjacent structure for the case of deep excavation? Is it worth to include stiffness of the nearby structure?
- Is it possible to translate the displacement criteria into criteria for horizontal wall displacement? Which developments are needed to formulate practical guidelines for limiting values of wall displacement?
- What is the accuracy needed for the prediction of wall displacements in relation with settlement criteria for nearby structures?
- How can the increasing distance be bridged between advanced numerical models, including difficult parameter evaluation, with daily design practice?

Answers to these questions should contribute in ranking the needs of theoretical developments and of practical implementation in the design of these developments to allow for increasingly reliable and economic design of deep excavations in urban environment.

REFERENCES

Boscardin, M.D. & Cording, E.J.1989. Building response to excavation induced settlement. *Jn. Geotech. Eng.*, ASCE, 115(1): 1-21.

Clough, W.G., Smith, E.M. & Sweeney, B.P. 1989. Movement control of excavation support systems by iterative design. *Proc A.S.C.E. Foundation Engineering: Current principles and Practice* Vol 2, pp 869-884

Poulos, H.G., Carter, J.P. & Small, J.C. 2001. Foundation and retaining structures- research and practice. Proc 15th Int. Conf. on Soli Mech and Found Eng, Istanbul, vol 4 2527-2606

Schweiger, H.F. 1998. Results from two geotechnical benchmark problems. *Proc. 4th European Conf. Numerical Methods in Geotechnical Engineering.* Cividini, A. (ed.), 645-654.